PB2000-108114

Report No. CDOT-R&D-SM-99-4

Final Report

INITIAL CURING OF PORTLAND CEMENT CONCRETE CYLINDERS

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DEPARTMENT OF TRANSPORTATION

December 1999

COLORADO DEPARTMENT OF TRANSPORTATION

RESEARCH BRANCH

Technical Report Documentation Page

1. Report No. CDOT-R&D-SM-99-4	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle INITIAL CURING OF PORTLAND CEMENT CONCRETE CYLINDERS		**5. Report Date** December 1999
		6. Performing Organization Code
7. Author(s) Reza Akhavan & Monte Malik		**8. Performing Organization Report No.** CDOT-R&D-SM-99-4
9. Performing Organization Name and Address Colorado Department of Transportation Concrete/Physical Properties Unit 4201 E. Arkansas Ave. Denver, CO 80222		**10. Work Unit No. (TRAIS)**
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Colorado Ready Mixed Concrete Association and the Colorado Department of Transportation Concrete/Physical Properties Unit 4201 E. Arkansas Ave. Denver, CO 80222		**13. Type of Report and Period Covered** Final Report
		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Colorado Ready Mixed Concrete Association (CRMCA).

16. Abstract

Colorado Ready Mixed Concrete Association (CRMCA) task force members feel that AASHTO T 23-93, Section 9.2.1; "Standard Specification for Making and Curing Concrete Test Specimens in the Field" allows wide variance when describing the initial curing condition requirements. Absence of specific direction, in regards to initial curing, leads to non-uniform practices by field technicians and inconsistent 28-day compressive strength results. It is believed that this inconsistency has led to increased costs associated with unnecessary over-design of Portland Cement Concrete (PCC) mixes, further testing of in-place PCC and the time-consuming claims process.

CRMCA Technical Education Committee organized a task force to study the effect of various initial curing conditions on the compressive strength of concrete cylinders. Five different initial curing conditions and two in-place conditions were tested.

Initially curing PCC test cylinders in saturated limewater provides more consistent surrounding temperature, a record of the surrounding temperature and rigidly conforms to T 23-93, preventing any moisture loss. This is a practical curing method that leads to more consistent 28-day compressive strengths. More consistent results will reduce costs associated with unnecessary over-design of PCC mixes, further testing of in-place PCC and the time-consuming claims process.

Implementation/Recommendations

Portland Cement Concrete cylinders, for checking the Adequacy of Laboratory Mixture Proportions for Strength or as the Basis for Acceptance or Quality Control, shall be initially cured (24 to 48 hours) by full immersion in saturated limewater (lime concentrations as per AASHTO M 201-96).

17. Key Words concrete cylinders, initial curing, saturated limewater, 28-day compressive strength		**18. Distribution Statement** No restrictions.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages**	**22. Price**

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INITIAL CURING OF PORTLAND CEMENT CONCRETE CYLINDERS

By

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CDOT-R&D-SM-99-4

Prepared by
Colorado Department of Transportation
Concrete/Physical Properties Unit
Research Branch

Sponsored by the
Colorado Department of Transportation
In Cooperation with the
Colorado Ready Mixed Concrete Association

December 1999

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ACKNOWLEDGEMENTS

Thanks to the Colorado Ready Mixed Concrete Association (CRMCA) task force members for their time, personnel and commitment to this study. The research team would like to express appreciation to Lafarge, Inc. for supplying the test site and concrete. Special thanks to the Colorado Department of Transportation (CDOT) personnel at Staff Materials, Concrete/Physical Properties Unit, for accommodating the extra work involved in storing and testing the cylinders. Also thanks to all the other members of CDOT who took the time to review the study and provide additional information and comments.

Thanks to the task force members for facilitating this study and review of this report. The task force research team consisted of Gerrit Lansing, of Mountain Cement; Chris Hinton, of CAMAS Colorado, Inc.; Matt Nilsen, of Lafarge, Inc.; and Greg Lowery, of the Colorado Department of Transportation.

EXECUTIVE SUMMARY

The Portland Cement Concrete (PCC) industry and the Colorado Department of Transportation (CDOT) have experienced discrepancies in compressive strength results of concrete test cylinders. Some field results have misrepresented strength of Portland Cement Concrete, as delivered to the project and in-place. Colorado Ready Mixed Concrete Association (CRMCA) task force members felt that AASHTO T 23-93, Section 9.2.1; "Standard Specification for Making and Curing Concrete Test Specimens in the Field" allowed too much variance when describing the initial curing condition requirements. Absence of specific direction, in regards to initial curing, leads to non-uniform practices by field technicians and inconsistent 28-day compressive strength results. It is believed that this inconsistency has led to increased cost associated with unnecessary over-design of Portland Cement Concrete (PCC) mixes, further testing of in-place PCC and the time-consuming claims process.

Concrete test cylinders were subjected to five different initial curing conditions and two in-place conditions. These represented procedures described in AASHTO T 23-93, section 9.2.1 and other extremes existing in the field.

Initially curing PCC test cylinders in saturated limewater provides more consistent surrounding temperature, a record of the surrounding temperature and rigidly conforms to T 23-93 section 9.2.1, preventing any moisture loss. This is a practical curing method that leads to more consistent 28-day compressive strengths. More consistent results will reduce costs associated with unnecessary over-design of PCC mixes, further testing of in-place PCC and the time-consuming claims process.

IMPLEMENTATION

Portland Cement Concrete cylinders, for checking the Adequacy of Laboratory Mixture Proportions for Strength or as the Basis for Acceptance or Quality Control, shall be initially cured by full immersion in saturated limewater (lime concentration as per AASHTO M 201-96). The water shall be maintained between 60°F and 80°F, for the initial 24 to 48 hours. Specifying a Field Laboratory Class 2, as per Standard Plans, Colorado Department of Transportation, November 1992, can facilitate this. When a Field Laboratory Class 2 is impractical or not specified, a watertight container (curing tank) with a lid, having a volume twice that of the maximum volume of cylinders to be initially cured at one time, may be used. The curing tank shall be filled, with saturated limewater (lime concentration as per AASHTO M 201-96). The curing tank shall be equipped with a thermostatically controlled electric heater capable of maintaining the water in the tank at 60°F to 80°F and a recording thermometer, calibrated every six months, with its bulb in the storage water. The temperature logs shall be kept with the field sheet(s) (CDOT Form 82).

When a field trailer is not available the curing tank shall be buried or insulated if necessary and kept out of direct sunlight. This will minimize water temperature fluctuation. When electrical service is not available a maximum-minimum thermometer shall be submerged in the center of the tank to monitor the water temperature. The maximum-minimum temperature shall be read and recorded twice a day and kept with/on the field sheet(s) (CDOT Form 82).

Recommendation presented to and approved by CDOT's Materials Advisory Committee

The Department's Field Materials Manual for 2000 shall include the following text in the Remarks column of the Frequency Guide for Minimum Materials Sampling, Testing, and Inspection: Pay Item 412 and 601

T-23*

***Delete sentences 1-4 & 6 of AASHTO T 23-93[1] section 9.2.1 note 2 and replace with:**

Specimens shall be initially cured by full immersion in saturated limewater, with lime concentrations as per AASHTO M 201-96. Water temperature shall be recorded by a continuous recording thermometer, calibrated every six months, or maximum-minimum thermometer read and recorded, on/with CDOT Form 82, twice a day.

When a field trailer is not available the curing tank shall be buried or insulated if necessary.

Pay Item 608 and 609

Initial water cure as per 601, or as directed by the Engineer.

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1.0 INTRODUCTION

1.1 Overview

The concrete industry believes that inconsistent initial curing conditions of Portland Cement Concrete (PCC) test cylinders produce inconsistent and non-representative 28-day compressive strength results. This increases costs due to further testing of in-place concrete and unnecessary over-design of PCC mixes. The Technical Education Committee of the Colorado Ready Mixed Concrete Association (CRMCA) reviewed a 1995 study conducted by the New Mexico Ready Mix Concrete & Aggregates Association. (1) The study compared compressive strength results of cylinder casting from different labs and also different initial 24hr curing conditions of concrete test cylinders. In a similar effort, CRMCA organized a task force to study the affect of various initial 24hr curing conditions on the compressive strength of concrete test cylinders. The task force members were from Mountain Cement Company; Construction, Aggregates, Materials And Services (CAMAS Colorado, Inc.); Lafarge, Inc. (formerly Western Mobile); the City of Aurora; GTG Geotechnical Services LTD. (PSI); Ready Mixed Concrete Co.; and the Colorado Department of Transportation (CDOT). The task force members felt that AASHTO T 23-93, Section 9.2.1 & note 2; "Standard Specification for Making and Curing Concrete Test Specimens in the Field" was nebulous when describing the initial curing condition requirements. Absence of specific direction in AASHTO T 23-93, in regards to initial curing, leads to non-uniform practice by field technicians. This could lead to inconsistent 28-day compressive strength results.

1.2 Objective

To compare 28-day compressive strength results from five different initial 24hr curing conditions and in-place PCC. Prepare a report recommending a single initial curing method and an alternate method.

2.0 PLANNING

The curing conditions represented the procedures described in AASHTO T 23-93, Section 9.2.1 & note 2 and other extremes existing in the field. Molded cylinders set in the slab for the first 24 hours then standard cured in a moist room represented the in-place concrete. Another set was cured in the slab for 28 days. Cores were taken and tested. The only variable between the cylinder sets was the initial curing condition.

The following are descriptions of the initial curing conditions:

- Condition #1: air-cured at ambient humidity, between 60°F and 80°F, no direct sunlight
- Condition #2: 100% saturated in a lime water tank at 73°F(+-3°F)
- Condition #3: ambient humidity, between 90 °F and 110 °F. The cylinders were placed in a 7' x 7' fully enclosed room with a thermostatically controlled electric radiant heater. This simulated a hot field trailer or cure box on site during the summer.
- Condition #4: ambient humidity, between 29 °F and 43 °F. The cylinders were placed in a refrigerator to simulate possible field trailer or cure box conditions on site during the winter.
- Condition #5: molded and capped 4"x 8" cylinders placed inside 6"x 12" molds. The space between the molds was filled with Persolite. The mold combinations were set in a six-inch thick slab and cured by covering with insulating blankets for five days (see Figures 1 & 2).
- In Slab 28 Days: represented in-place Portland Cement Concrete

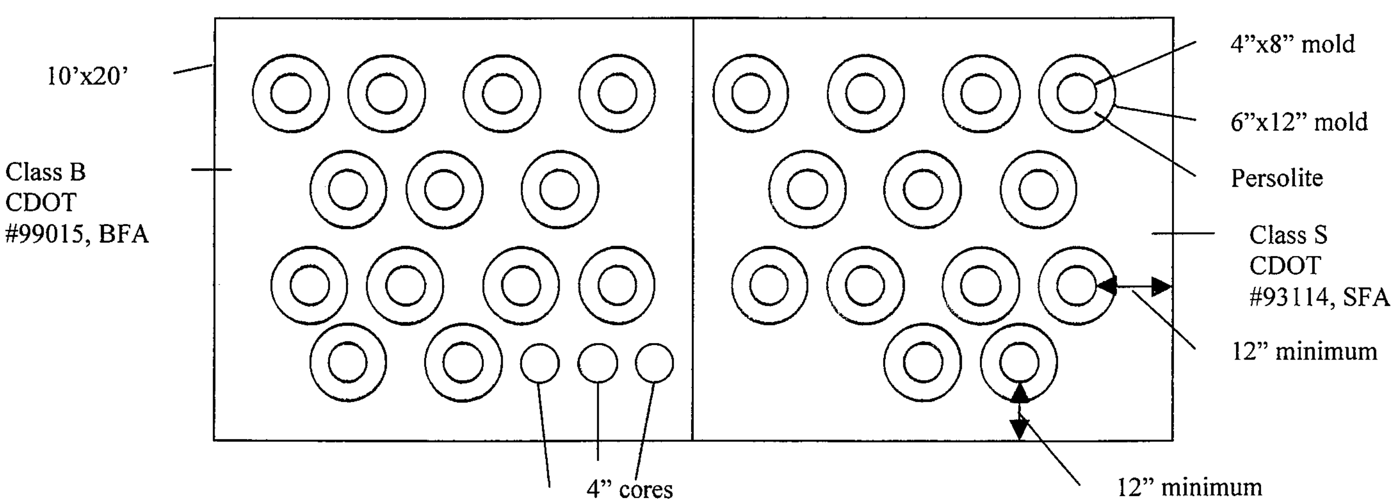


Figure 1. Condition #5; slab on grade (plan view, not shown to scale).

Two CDOT mixes were used: Class B, #99015 BFA (3000psi) and Class S40, #93114 SFA (5800psi). See Appendix A for mix design information.

Ten 4"x 8" cylinders were molded for each mix design and condition; the molds were plastic single use. Two cylinders were tested for each condition, at 1, 3 and 7 days; three cylinders were tested at 28 days. One cylinder, for each condition, contained a thermocouple. The thermocouples were connected to maturity meters and data loggers to record the internal temperature of the cylinders. The 24-hour temperature log is shown in Figure 7.

Figure 2. Initial curing condition #5.

3.0 PROCESS

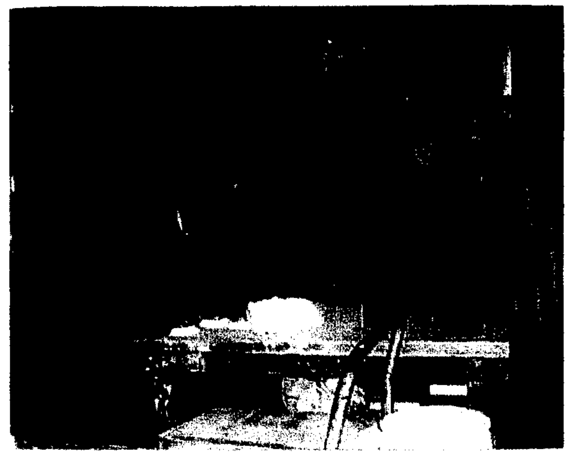


Figure 3. Molding cylinders.

The cylinders and slab were cast and initially cured at the Lafarge Ready Mix Plant, Denver, Colorado on February 15,1999. Weather conditions were 50°F and overcast. Four yards of each class of PCC were shrink-mixed then delivered to the casting/testing area in a Revolving Drum Truck Mixer. The PCC was sampled in general accordance with AASHTO T 141-93, "Standard Specification for Sampling Freshly Mixed Concrete" and cylinders molded in general accordance with AASHTO T 23-93, "Making and Curing Concrete Test Specimens in the Field". All cylinders were uniformly molded, finished and capped. Following 24hrs(+-1hr) of initial curing the cylinders were packed in sand, transported to the Colorado Department of Transportation Central Lab (AASHTO Accredited), molds removed, and standard cured in a moist room as per AASHTO T 23-93.

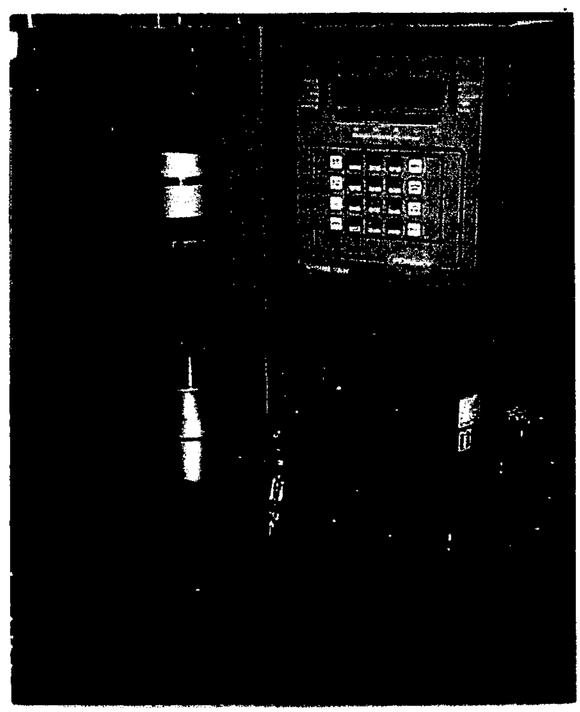


Figure 4. Forney System 2000.

Compressive cylinder tests were performed by the same technician, ACI Lab Technician Grade I & II certified, at 1, 3, 7 and 28 days. The tests were performed in general accordance with AASHTO T 22-92, "Compressive Strength of Cylindrical Concrete Specimens" and Colorado Procedure 66-90, "Method of Test For Determining Compressive Strength of Cylindrical Concrete Specimens 4"x 8" (102mm x 203mm) Using Steel End Caps and Reusable Neoprene Pads". The cylinders were tested on a Forney System 2000 testing machine. CAL TEST, INC. in accordance with ASTM E4-94 calibrated the testing machine.

The same two sets of steel end caps and neoprene pads were used; the pads were new and did not exceed 100 breaks. The tops of all cylinders were cut, to ensure uniform surfaces, prior to being tested; all length-to-diameter ratios were above 1.8.

Four-inch cores were taken by CDOT on March 17, 1999 (30 days) and tested on March 18, 1999. Cores were tested in general accordance with AASHTO T 24-93, "Standard Specification for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete" as modified by Colorado Procedure 65-91, "Method of Evaluating Low Strength Test Results of Concrete Cylinders" (CP 65-91). The cores were sawed, capped, and tested by the same technician, on a SATEC Universal Testing Machine. CAL TEST, INC. in accordance with ASTM E4-94 calibrated the testing machine. This data was used to compare strength results from cores and cylinders (see Figure 5 and Appendix B-2, B-3).

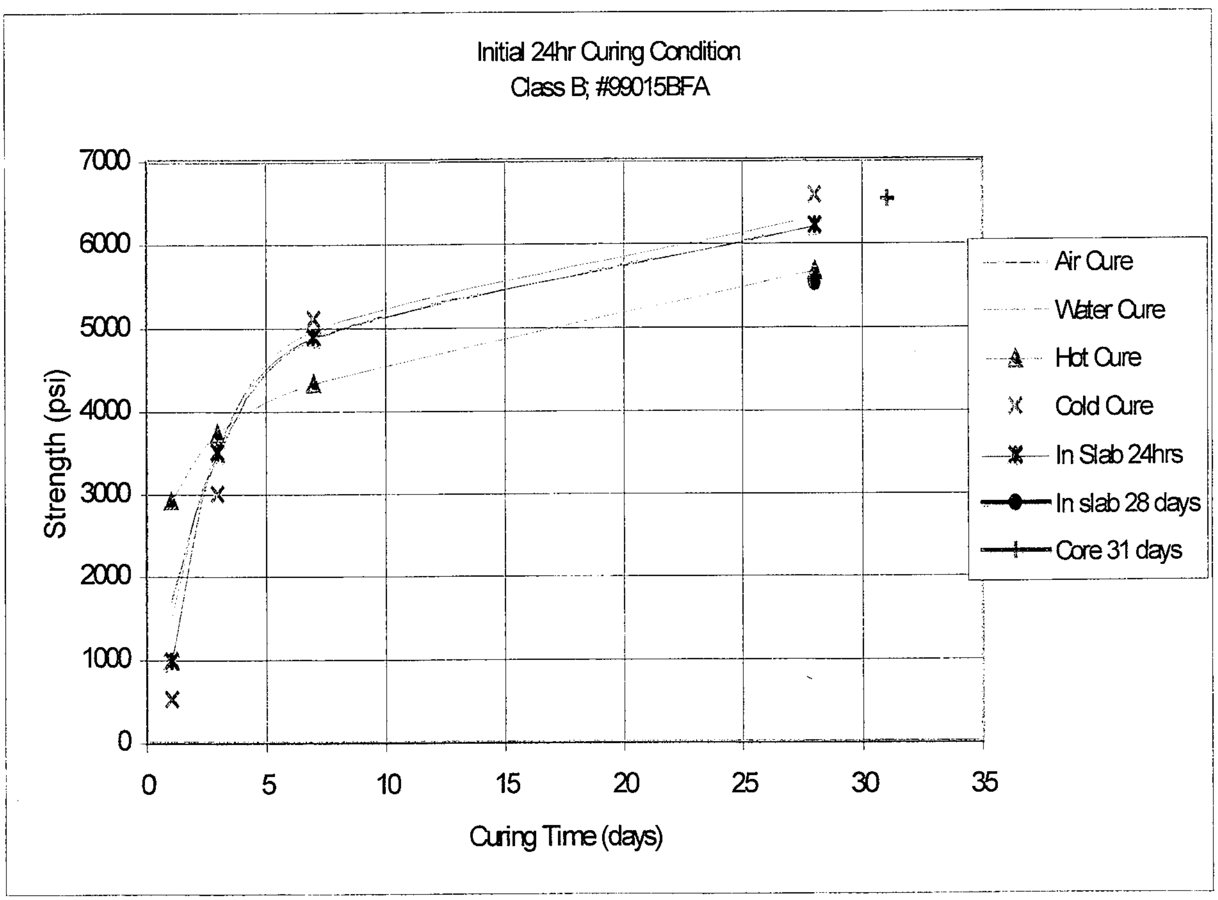


Figure 5. Class B Portland Cement Concrete cylinder compressive strengths.

4.0 RESULTS

4.1 Physical Properties of Plastic Concrete

Table A. Physical properties of plastic concrete.

	Class B	Class S
Slump	2.00in.	1.75in.
Air	6.2%	4.2%
Unit Weight	141.2lbs/ft^3	144.8lbs/ft^3
Concrete Temp.	62°F	68°F
W/C Ratio	0.37	0.30

4.2 Class B

The cold initial cure developed the highest compressive strength at 28 days; 6567psi. The cylinders cured in the slab for 28 days developed the lowest compressive strength at 28 days; 5510psi. The strength range was 1057psi. The range between the air-cure (60°F to 80°F) and water-cure was 93psi. The air-cure (60°F to 80°F) and in slab cylinder strengths are 1% below the water-cured cylinders. The hot-cure produced strengths 10% below the water-cured cylinders. The in slab (28 days) cylinders produced strength 12% below the water-cured cylinders. Both cold-cure and cores produced strengths 4% higher than the water-cured cylinders. The compressive strength gained over time is shown in Figure 5.

The strength differences, between the water-cured cylinders and the other cylinder curing conditions, are shown in Table B.

Table B. Class B; comparison of 28-day compressive strengths to water-cure.

Strengths Compared to Water-Cured Cylinders			
Cure Condition	This Study	New Mexico Study[1][2]	1983 Study[2]
In slab 28 days	-12%		
Initial hot-cure	-10%	-15% to –19%	
Initial in slab-cure	-1%		
Initial air-cure	-1%		-2.8% to –9.7%
Initial cold-cure	+4%	+4% to +5.8%	
Core	+4%		

4.3 Class S

The cold initial cure developed the highest compressive strength at 28 days; 9047psi. The hot initial cure developed the lowest compressive strength at 28 days; 7733psi. The strength range was 1314psi. The range between the air-cure (60°F to 80°F) and water-cure was 340psi. The air-cure (60°F to 80°F) cylinder strength was 4% below the water-cured cylinders. The in slab (28 days) cylinders produced strength 8% below the water-cured cylinders. The hot-cure produced strengths 12% below the water-cured cylinders. The in slab condition (24hrs) produced strengths 2% above the water-cure condition. And the cold condition produced strengths 3% higher than the water-cure condition. The compressive strength gained over time is shown in Figure 6.

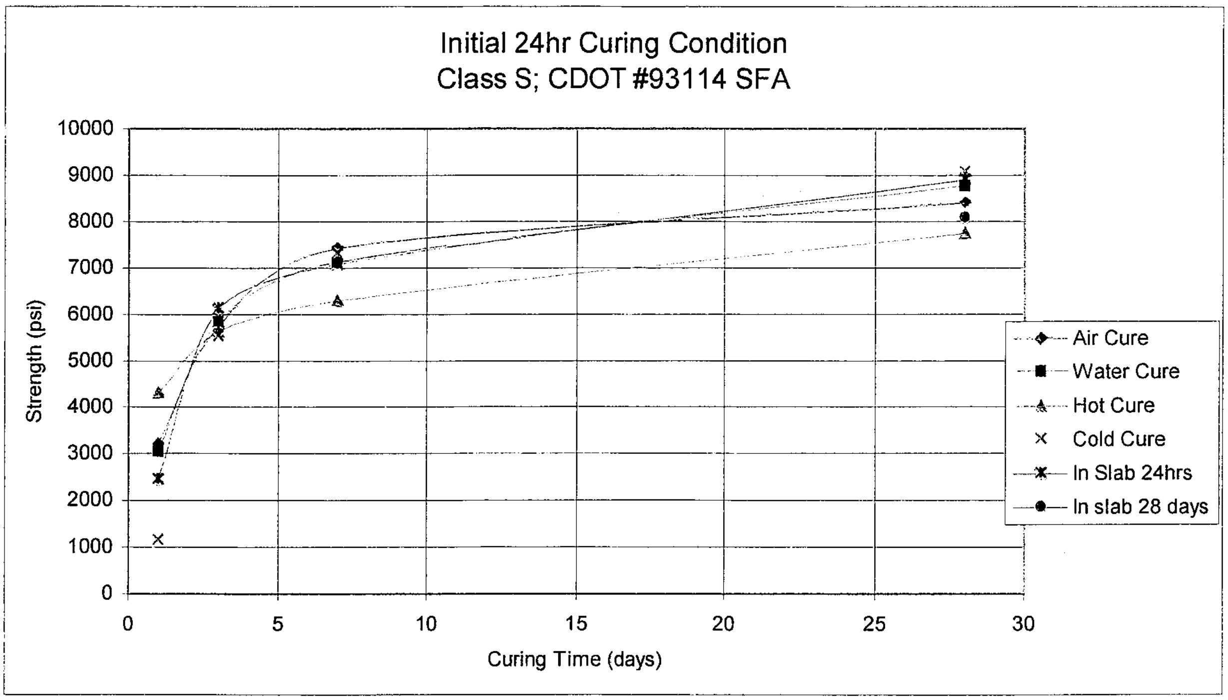


Figure 6. Class S PCC cylinder compressive strengths

The strength differences, between the water-cured cylinders and the other cylinder curing conditions, are shown in Table C.

Table C. Class S; comparison of 28-day compressive strengths to water-cure.

Strengths Compared to Water-Cured Cylinders			
Cure Condition	This Study	New Mexico Study[(1)(2)]	1983 Study[(2)]
Initial hot-cure	-12%	-15% to –19%	
In slab 28 days	-8%		
Initial air-cure	-4%		-2.8% to –9.7%
Initial in slab-cure	+2%		
Initial cold-cure	+3%	+4% to +5.8%	

5.0 EVALUATION AND RECOMMENDATIONS

5.1 Evaluation

It should be noted that field conditions are not as consistent and controlled as the conditions in this research. Lack of specifying a single initial curing condition, in AASHTO T 23-93, increases the variability of representative cylinders and the range of 28-day compressive strengths. It is believed that inconsistent 28-day compressive strengths have led to increased costs associated with unnecessary over-design of PCC mixes, further testing of in-place Portland Cement Concrete and the time consuming claims process.

Initially curing PCC test cylinders in a lime water tank reduces the internal temperature gradient of the cylinders; this is shown in Figure 7. The volume of water insulates the cylinders from extreme temperature fluctuations and moisture loss, which conforms to AASHTO T 23-93, section 9.2.1. The cylinders experience more consistent surrounding temperatures as does a mass of concrete. The water temperature can be controlled, monitored, and a permanent record logged.

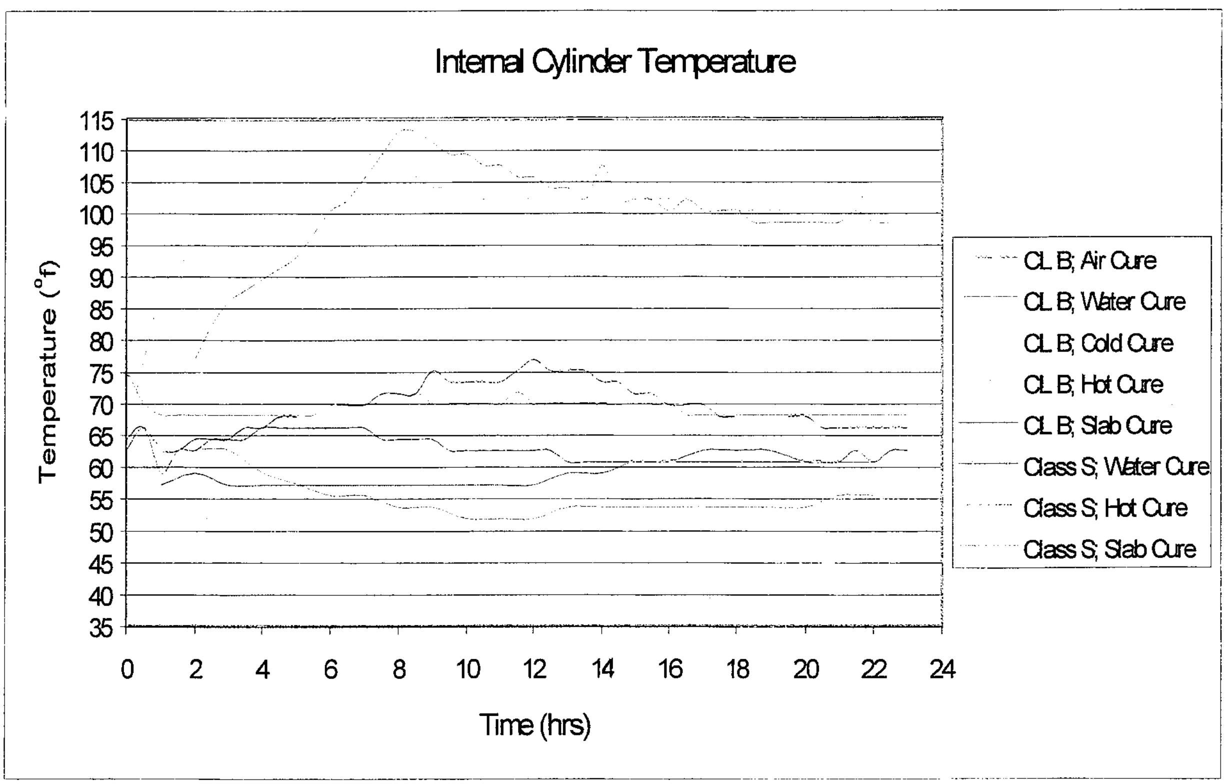


Figure 7. Initial 24hr internal cylinder temperatures.

The lower temperature gradient may allow better crystalline growth during the initial hydration of the concrete. This may lead to lower internal cylinder stresses, during initial hydration, (less thermo-expansion and contraction) and improved bonding of the concrete components. Also no moisture leaves the cylinder.

In October 1996, Project HB 0253-133 had compressive strength discrepancies between concrete test cylinders. [(4)] On November 8, 1996 CTL, Ready Mixed and Aguirre Engineers molded four sets of cylinders; two sets were initially cured in a water tank and two sets initially cured on the field trailer floor. Both, water tank cured, cylinder sets produced seven-day average compressive strengths of 38.4MPa. The floor-cured cylinder sets produced seven-day average compressive strengths of 34.0MPa and 33.9MPa. [(5)] This showed, approximately, a 12% strength discrepancy; the mix was required to attain a minimum of 35MPa. Region six strongly recommends structural and pavement concrete cylinders be initially cured in a water tank that has a recording thermometer. [(6)] Kaye Stephenson, Region 6 Materials, says it has reduced compressive strength discrepancies between commercial labs and the state lab. This has led to decreased costs associated with investigating the low compressive strength results and time spent in the claims process.

5.2 Recommendations

Portland Cement Concrete cylinders, for checking the Adequacy of Laboratory Mixture Proportions for Strength or as the Basis for Acceptance or Quality Control, shall be cured in a limewater tank (set up as per ASTM C 511-97), at 60°F to 80°F, for the initial 24 to 48 hours. Cylinders initially cured this way will more rigidly conform to T 23-93, 9.2.1 (note 2), allowing no moisture loss. Specifying a Field Laboratory Class 2, as per Standard Plans, Colorado Department of Transportation, November 1992, can facilitate this. When a Field Laboratory Class 2 is impractical or not specified, a watertight container (curing tank) with a lid, having a volume twice that of the maximum volume of cylinders to be initially cured at one time, may be used. The curing tank shall be filled, with saturated limewater, as per ASTM C 511-97, to a level one and a half times that (or more) of the largest cylinder height. The curing tank shall be equipped with a thermostatically controlled electric heater capable of maintaining the water in the tank at 70°F (+-4°F) and a recording thermometer with its bulb in the storage water. The temperature logs shall be kept with the field sheet(s) (CDOT #82).

When a field trailer is not available the curing tank shall be buried or surrounded by earth (or other suitable insulating material) and out of direct sunlight, to minimize water temperature fluctuation. When electrical service is not available a High/Low thermometer shall be used to monitor the water temperature. The high/low temperature shall be recorded twice a day and kept with/on the field sheet(s) (CDOT #82).

Recommendation presented to and approved by CDOT's Materials Advisory Committee

The Department's Field Materials Manual for 2000 shall include the following text in the Remarks column of the Frequency Guide for Minimum Materials Sampling, Testing, and Inspection: Pay Item 412 and 601

T-23*

***Delete sentences 1-4 & 6 of AASHTO T 23-93[1] section 9.2.1 note 2 and replace with:**

Specimens shall be initially cured by full immersion in saturated limewater, with lime concentrations as per AASHTO M 201-96. Water temperature shall be recorded by a continuous recording thermometer, calibrated every six months, or maximum-minimum thermometer read and recorded, on/with CDOT Form 82, twice a day.

When a field trailer is not available the curing tank shall be buried or insulated if necessary.

Pay Item 608 and 609

Initial water cure as per 601, or as directed by the Engineer.

Repeat the study

- Accumulate more corroborating data
- Encourage CDOT/Consultant interaction prior to construction projects
- Familiarize consultant personnel with CDOT paper work
- Build communication between agency and supplier
- Hands on experience would reinforce the need/importance of a uniform state wide initial curing method
- Remote areas would have input into a feasible alternate initial curing condition
- Possible problems: Consistent and uniform repeatability, requires diligent oversight

REFERENCES

1. Montoya, Tony. "Hot Weather Comparison Program; Fresh Concrete Testing & Initial Curing Practices." Report to General Membership New Mexico Ready Mix Concrete & Aggregates Association (NMRMCAA), April 22, 1995.

2. Server, Jeff. "Concrete Strength Meeting." HB 0253-133, I-25 & US 36 HOV Phase I, November 7, 1996.

3. Server, Jeff. "Concrete Strength Meeting." HB 0253-133, I-25 & US 36 HOV Phase I, November 26, 1996.

4. Aschenbrener, Tim. "Initial Curing of Concrete Cylinders." Memo to Resident Engineers and Head Testers, August 14, 1997.

Appendix A

LAFARGE

IDENTIFICATION NO.:M 3692 METRIC (SCBF, Metro South)
LCM Lab No.: 8164, Trial Date 11-23-98
CDOT Ref No.: 99015

MIX PROPORTIONS:

		(PER CUBIC YARD)	(PER CUBIC METER)
Cement	ASTM C-150	452 lbs.	268 kgs.
Fly Ash, Class C	ASTM C-618	113 lbs.	67 kgs.
Sand	ASTM C-33	1240 lbs.	736 kgs.
Size # 67 Agg.	ASTM C-33	1800 lbs.	1068 kgs.
AEA	ASTM C-260	3.5 ozs.	135 mls.
WRA	ASTM C-494	17.0 ozs.	657 mls.
Water	ASTM C-94	248 lbs.(29.8 gal.)	147 kgs.(147 ltrs.)

The above weights are based upon aggregates in a saturated, surface dry condition. Batch plant corrections must be made for moisture in aggregates.

PHYSICAL PROPERTIES OF MIX:
(From Laboratory Trial Mix # 8164)

	ENGLISH	METRIC	LCM SPECS
Slump	3.00 "	76 mm.	4.50" Max.
Air Content	5.6 %	5.6 %	5 - 8 %
Unit Weight	141.4 pcf	2265 kg/cu.m.	
Water/Cement Ratio	0.44	0.44	0.53
Yield	27.25	1.01	

COMPRESSIVE STRENGTH:
(From Laboratory Trial Mix # 8164)

ENGLISH (psi)			METRIC (MPa)		
3 Day	7 Day	28 Day	3 Day	7 Day	28 Day
2400	4050	5660	16.5	27.9	39.0
2400	4360	5690	16.5	30.1	39.2
2370	4470	5470	16.3	30.8	37.7
2390	4295	5605	16.5	29.6	38.6

Lafarge Construction Materials
U.S. Western Region

IDENTIFICATION NO. : 6807 SCS ERM (6 K)
WMI Lab No.: 3120
CDOT REF. NO.: 93114

MIX PROPORTIONS :

		(PER CUBIC YARD OF CONCRETE)
Cement	ASTM C-150	560 lbs.
Fly Ash	ASTM C-618	140 lbs.
Sand	ASTM C-33	1220 lbs.
Size #67 Agg.	ASTM C-33	1780 lbs.
AEA	ASTM C-260	1.6 ozs.
WRA	ASTM C-494	21.0 ozs.
HRWR	ASTM C-494	70.0 ozs.
Water	ASTM C-94	225 lbs.(27.0 gal.)

The above weights are based upon aggregates in a saturated, surface dry condition. Batch plant corrections must be made for moisture in aggregates.

PHYSICAL PROPERTIES OF TRIAL MIX :

		WMI SPEC
Slump (in.)	7.25"	4-6"
Air Content (%)	7.5%	5-8%
Unit Weight (pcf)	142.4 pcf	
Water/Cement Ratio	0.32	0.38

COMPRESSIVE STRENGTH (psi)
(From Laboratory Trial Mix)

3 Day	7 Day	28 Day
4830	5750	7290
5180	5770	6970
5005	5860	7210
	5790	7155

WESTERN MOBILE INC.

Appendix B

Research: Initial Curing Condition of Concrete Test Cylinders

Class B; CDOT #99015		Design Strength(psi):			3000					
	Days	Ave.		Max		Ave.	Delta			
Cylinder	Cured	Diam(in)	Area(in^2)	Load(lbs.)	Strength(psi.)	Strength(psi.)	Strength(psi.)	σ(psi)	V	
1B	1	3.99	12.5036	21140	1690					
1B	1	3.99	12.5036	21290	1702	1696	12	8	0.5	
2B	1	3.99	12.5036	19070	1525					
2B	1	4.00	12.5664	17900	1424	1475	101	71	4.8	
3B	1	4.00	12.5664	38690	3078					
3B	1	4.00	12.5664	34920	2778	2928	300	212	7.2	MAX
4B	1	3.99	12.5036	6730	538					
4B	1	3.99	12.5036	6050	483	511	55	39	7.6	
5B	1	3.99	12.5036	11620	929					
5B	1	3.99	12.5036	12700	1015	972	86	61	6.3	
1B	3	3.99	12.5036	41060	3283					
1B	3	3.99	12.5036	45130	3609	3446	326	231	6.7	
2B	3	3.99	12.5036	44660	3571					
2B	3	3.99	12.5036	43530	3481	3526	90	64	1.8	
3B	3	4.00	12.5664	47680	3794					
3B	3	4.00	12.5664	46250	3680	3737	114	81	2.2	MAX
4B	3	3.99	12.5036	36540	2922					
4B	3	3.99	12.5036	38280	3061	2992	139	98	3.3	
5B	3	3.99	12.5036	43710	3495					
5B	3	3.99	12.5036	43540	3482	3489	13	9	0.3	
1B	7	3.99	12.5036	59930	4790					
1B	7	3.99	12.5036	61640	4930	4860	140	99	2.0	
2B	7	3.99	12.5036	62960	5040					
2B	7	3.99	12.5036	60370	4830	4935	210	148	3.0	
3B	7	4.00	12.5664	54850	4360					
3B	7	4.00	12.5664	54170	4310	4335	50	35	0.8	
4B	7	3.99	12.5036	61770	4940					
4B	7	4.00	12.5664	65730	5230	5085	290	205	4.0	MAX
5B	7	3.99	12.5036	60510	4840					
5B	7	3.99	12.5036	61560	4920	4880	80	57	1.2	
1B	28	3.99	12.5036	75390	6030					
1B	28	3.99	12.5036	80310	6420					
1B	28	3.99	12.5036	76770	6140	6197	390	201	3.2	
2B	28	3.99	12.5036	78500	6280					
2B	28	3.99	12.5036	79290	6340					
2B	28	4.00	12.5664	78560	6250	6290	90	46	0.7	
3B	28	4.00	12.5664	69560	5540					
3B	28	4.00	12.5664	69400	5520					
3B	28	4.00	12.5664	74930	5960	5673	440	248	4.4	
4B	28	4.00	12.5664	82820	6590					
4B	28	3.99	12.5036	79820	6380					
4B	28	3.99	12.5036	84180	6730	6567	350	176	2.7	MAX
5B	28	3.99	12.5036	81200	6490					
5B	28	3.99	12.5036	80600	6450					
5B	28	3.99	12.5036	70950	5670	6203	820	462	7.5	
In slab	28	3.99	12.5036	64670	5170					
In slab	28	3.99	12.5036	75990	6080					
In slab	28	3.99	12.5036	66080	5280	5510	910	497	9.0	
Core 6A	31	4.01	12.6293	93700	6529					
Core 6B	31	4.00	12.5664	89000	6232					
Core 6C	31	4.01	12.6293	97400	6787	6516	555	278	4.3	

<u>Curing condition; first 24hrs</u>: 1 = 60 °F to 80°F air cure 2 = 73°F 100% saturated 3 = 90°F to 110°F

4 = 40°F(+-5°F) 5 = Inplace; ambient temp.

Curing condition; first 24hrs	Class B	
1 = 60°F to 80°F air cure	3 = 90°F to 100°F air cure	5 = Ambient temperature; air cure
2 = 73°F 100% saturated	4 = 40°F(+-5°F) air cure	

Curing Condition	Days Cured	Strength(psi)	Δ% Strength from Cond.#2	Curing Condition	Days Cured	Strength(psi)	Δ% Strength from Cond.#2
1	1	1696		2	1	1474.5	
1	3	3446		2	3	3526	
1	7	4860		2	7	4935	
1	28	6197	-1	2	28	6290	0
Curing Condition	**Days Cured**	**Strength(psi)**	**Δ% Strength from Cond.#2**	**Curing Condition**	**Days Cured**	**Strength(psi)**	**Δ% Strength from Cond.#2**
3	1	2928		4	1	510.5	
3	3	3737		4	3	2991.5	
3	7	4335		4	7	5085	
3	28	5673	-10	4	28	6567	4
Curing Condition	**Days Cured**	**Strength(psi)**	**Δ% Strength from Cond.#2**	**Curing Condition**	**Days Cured**	**Strength(psi)**	**Δ% Strength from Cond.#2**
5	1	972		In Slab	28	5510	-12
5	3	3488.5		Core	31	6516	4
5	7	4880					
5	28	6203	-1				

CLASS B; CDOT #99015 Slab On Grade Wire Bucket Wt.(g)= 1875.8 at 73°F

Core	Diam. (in)	Area (in^2)	Cut Length (in)	Capped Length (in)	L/D Check	Wet Weight (g)	Dry Weight (g)	Load (lbs.)	Comp. Strength(psi)	Length to Diameter	Strength Correction Factor	Corrected Compressive Strength(psi)
6A	4.01	12.62928	3.97	4.21	Test	2960.6	1896.2	93700	7419	1.05	0.88	6529
6B	4	12.56637	4.03	4.26	Test	2956.9	1906.4	89000	7082	1.07	0.88	6233
6C	4.01	12.62928	3.97	4.19	Test	2955.3	1887.7	97400	7712	1.04	0.88	6787

Average Core Strength (psi)= 6516

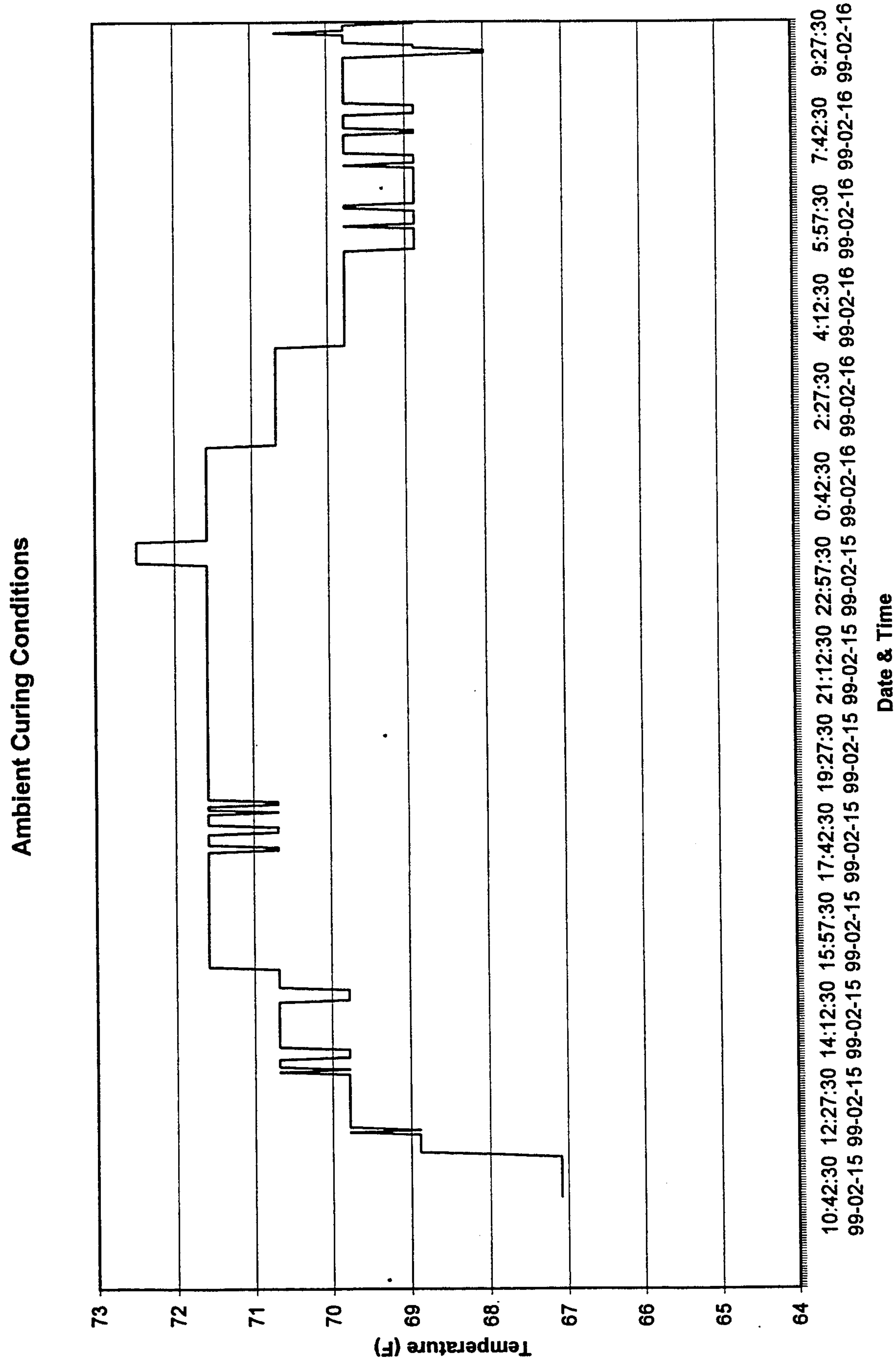
Research: Initial Curing Condition of Concrete Test Cylinders

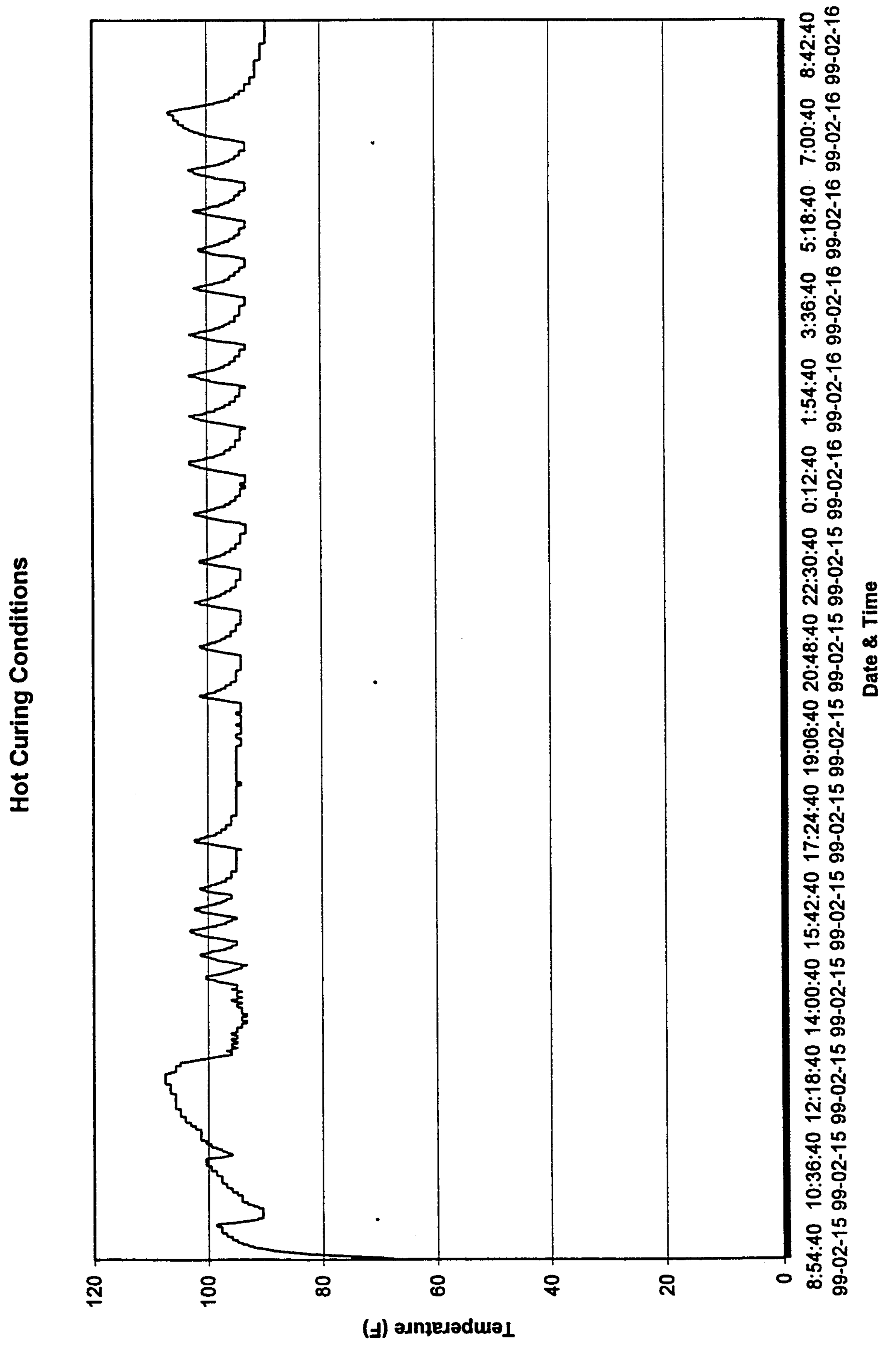
Class S; CDOT #93114	Design Strength(psi):	5800								
	Days	Ave.		Max		Ave.	Delta			
Cylinder	Cured	Diam(in)	Area(in^2)	Load(lbs.)	Strength(psi.)	Strength(psi.)	Strength(psi.)	σ(psi)	V	
1S	1	4.00	12.5664	41800	3326					
1S	1	4.00	12.5664	38380	3054	3190	272	192	6.0	
2S	1	4.00	12.5664	35980	2863					
2S	1	4.00	12.5664	39880	3173	3018	310	219	7.3	
3S	1	4.00	12.5664	51960	4134					
3S	1	4.00	12.5664	56080	4462	4298	328	232	5.4	MAX
4S	1	3.99	12.5036	13890	1110					
4S	1	3.99	12.5036	14420	1153	1132	43	30	2.7	
5S	1	3.99	12.5036	30280	2421					
5S	1	3.99	12.5036	30610	2448	2435	27	19	0.8	
1S	3	4.00	12.5664	72960	5805					
1S	3	4.00	12.5664	71270	5671	5738	134	95	1.7	
2S	3	4.00	12.5664	72800	5793					
2S	3	4.00	12.5664	73070	5814	5804	21	15	0.3	
3S	3	4.00	12.5664	71130	5660					
3S	3	4.00	12.5664	70300	5594	5627	66	47	0.8	
4S	3	3.99	12.5036	70100	5606					
4S	3	3.99	12.5036	67400	5390	5498	216	153	2.8	
5S	3	3.99	12.5036	77300	6182					
5S	3	3.99	12.5036	75460	6035	6109	147	104	1.7	MAX
1S	7	3.99	12.5036	91340	7310					
1S	7	4.00	12.5664	94490	7520	7415	210	148	2.0	MAX
2S	7	4.00	12.5664	90450	7200					
2S	7	4.00	12.5664	87820	6990	7095	210	148	2.1	
3S	7	4.00	12.5664	80280	6390					
3S	7	4.00	12.5664	77530	6170	6280	220	156	2.5	
4S	7	4.00	12.5664	97010	7720					
4S	7	3.99	12.5036	85320	6820	7270	900	636	8.8	
5S	7	3.99	12.5036	87120	6970					
5S	7	3.99	12.5036	89660	7170	7070	200	141	2.0	
1S	28	4.00	12.5664	102930	8190					
1S	28	4.00	12.5664	103670	8250					
1S	28	4.00	12.5664	110270	8770	8403	580	319	3.8	
2S	28	4.00	12.5664	110240	8770					
2S	28	4.00	12.5664	112360	8940					
2S	28	4.00	12.5664	107080	8520	8743	420	211	2.4	
3S	28	4.00	12.5664	100220	7980					
3S	28	4.00	12.5664	94080	7490					
3S	28	4.00	12.5664	97080	7730	7733	490	245	3.2	
4S	28	3.99	12.5036	106490	8520					
4S	28	3.99	12.5036	118560	9480					
4S	28	4.00	12.5664	114810	9140	9047	960	487	5.4	MAX
5S	28	3.99	12.5036	111920	8950					
5S	28	3.99	12.5036	114280	9140					
5S	28	3.99	12.5036	107580	8600	8897	540	274	3.1	
In slab	28	3.99	12.5036	102400	8190					
In slab	28	4.00	12.5664	94450	7520					
In slab	28	3.99	12.5036	105840	8460	8057	940	484	6.0	

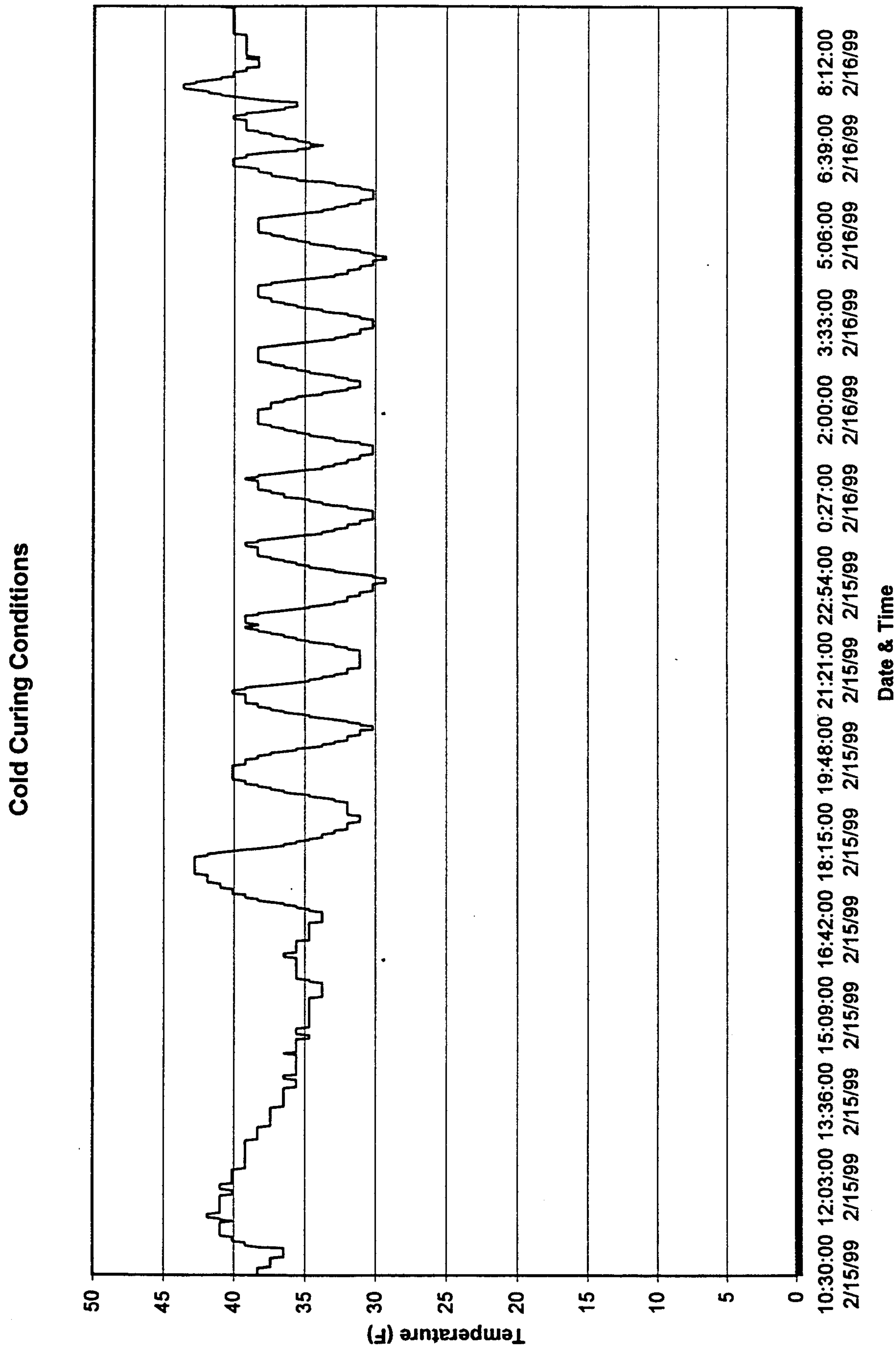
Curing condition; first 24hrs: 1 = 60 °F to 80°F air cure 2 = 73°F 100% saturated 3 = 90°F to 110°F
4 = 40°F(+-5°F) 5 = Inplace; ambient temp.

Curing condition; first 24hrs	Class S	
1 = 60°F to 80°F air cure	3 = 90°F to 100°F air cure	5 = Ambient temperature; air cure
2 = 73°F 100% saturated	4 = 40°F(+-5°F) air cure	

Curing Condition	Days Cured	Strength(psi)	Δ% Strength from Cond.#2	Curing Condition	Days Cured	Strength(psi)	Δ% Strength from Cond.#2
1	1	3190		2	1	3018	
1	3	5738		2	3	5804	
1	7	7415		2	7	7095	
1	28	8403	-4	2	28	8743	0
Curing Condition	Days Cured	Strength(psi)	Δ% Strength from Cond.#2	Curing Condition	Days Cured	Strength(psi)	Δ% Strength from Cond.#2
3	1	4298		4	1	1132	
3	3	5627		4	3	5498	
3	7	6280		4	7	7270	
3	28	7733	-12	4	28	9047	3
Curing Condition	Days Cured	Strength(psi)	Δ% Strength from Cond.#2	Curing Condition	Days Cured	Strength(psi)	Δ% Strength from Cond.#2
5	1	2435		In Slab	28	8057	-8
5	3	6109					
5	7	7070					
5	28	8897	2				


Ambient Curing Conditions
Temperature (F)
73
72
71
70
69
68
67
66
65
64
10:42:30 99-02-15
12:27:30 99-02-15
14:12:30 99-02-15
15:57:30 99-02-15
17:42:30 99-02-15
19:27:30 99-02-15
21:12:30 99-02-15
22:57:30 99-02-15
0:42:30 99-02-16
2:27:30 99-02-16
4:12:30 99-02-16
5:57:30 99-02-16
7:42:30 99-02-16
9:27:30 99-02-16
Date & Time


Hot Curing Conditions
Temperature (F)
0
20
40
60
80
100
120
8:54:40 99-02-15
10:36:40 99-02-15
12:18:40 99-02-15
14:00:40 99-02-15
15:42:40 99-02-15
17:24:40 99-02-15
19:06:40 99-02-15
20:48:40 99-02-15
22:30:40 99-02-15
0:12:40 99-02-16
1:54:40 99-02-16
3:36:40 99-02-16
5:18:40 99-02-16
7:00:40 99-02-16
8:42:40 99-02-16
Date & Time


Cold Curing Conditions
Temperature (F)
50
45
40
35
30
25
20
15
10
5
0
10:30:00 2/15/99
12:03:00 2/15/99
13:36:00 2/15/99
15:09:00 2/15/99
16:42:00 2/15/99
18:15:00 2/15/99
19:48:00 2/15/99
21:21:00 2/15/99
22:54:00 2/15/99
0:27:00 2/16/99
2:00:00 2/16/99
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Date & Time

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